Renewable and Sustainable Energy Reviews 14 (2010) 1059–1069

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review on packed bed solar energy storage systems

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ARTICLE INFO

Article history:
Received 31 August 2009
Accepted 20 October 2009

Keywords:
Sensible heat storage
Packed beds
Sphericity
Void fraction

ABSTRACT

Because of intermittent nature of solar energy, storage is required for uninterrupted supply in order to match the needs. Packed beds are generally used for storage of thermal energy from solar air heaters. A packed bed is a volume of porus media obtained by packing particles of selected material into a container. A number of studies carried out on packed beds for their performance analysis were reported in the literature. These studies included the design of packed beds, materials used for storage, heat transfer enhancement, flow phenomenon and pressure drop through packed beds. This paper presents an extensive review on the research carried out on packed beds. Based on the literature review, it is concluded that most of the studies carried out are on rocks and pebbles as packing material. A very few studies were conducted on large sized packing materials. Further no study has been reported so far on medium sized storage elements in packed beds.

Contents

1. Introduction

Conversion of solar energy into thermal energy is the easiest and the most widely accepted method. However, solar energy is a time dependent energy resource. Due to intermittent nature of solar energy, an energy storage unit is required to be attached with solar collectors to store energy for use when sunshine is not available. A storage system therefore constitutes an important component of the solar energy utilization system. A line diagram of a typical solar energy utilization system is shown in Fig. 1. The different forms of energy that can be stored include mechanical, electrical and thermal energy [1]. Thermal energy storage is of particular interest and significance in using this technique for solar thermal applications. Thermal energy can be stored as sensible heat, latent heat or chemical energy. An overview of major technique of storage of solar thermal energy is shown in Fig. 2. In sensible heat storage, heat is stored by increasing the storage medium temperature. In case of latent heat storage systems, the energy is stored in phase change materials. The heat is stored when the material changes phase from solid to a liquid. Thermo chemical storage is a technique, which involves chemical reactions.

Sensible heat storage is the most simple and inexpensive way of energy storage system although there are few advantages of phase change energy storage over sensible heat storage, but the technological and economical aspects make sensible heat storage superior. Packed beds represent the most suitable storage units for air-based solar system. A packed bed storage system consists of loosely packed solid material through which the heat transport fluid is circulated. Heated fluid (usually air) flows from solar collectors into a bed of graded particles from top to bottom in which thermal energy is transferred during the charging phase as shown in Fig. 3.

Coutier and Farber [2] mentioned that packed bed generally represents the most suitable energy storage unit for air based solar

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doi:10.1016/j.rser.2009.10.022

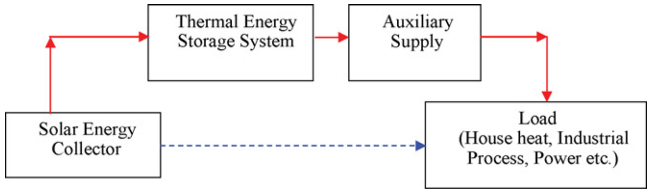

Fig. 1. Line diagram for a solar energy utilization system.

systems. During the charging mode, solar heated air is forced into the top of the container, i.e. upper plenum and then passes evenly down through the bed heating the storage and passes out through the lower plenum. Air is drawn off at the bottom and returned to the collectors. When energy is needed from storage, the airflow is reversed. Air at room temperature enters from bottom and flows to the top of the bed and is delivered into the building. After loosing heat in the room, the air from room comes to bottom of the bed and the cycle is repeated. The heat recovery from the bed is known as discharging phase. In order to avoid the heat losses the storage system is generally well insulated and installed near the solar collectors. The high heat transfer coefficient between the air and solid causes quick heat transfer from air to the solid. The particles near the entrance are heated but the temperature near the exit remains unchanged and the air comes out of the bed at a temperature very close to the initial bed temperature. As time progresses air at higher temperature passes through the bed and the exit air temperature begins to rise. When the bed is fully charged its temperature becomes uniform.

2. Packed bed energy storage system

Schematic of a packed bed energy storage system is shown in Fig. 3. A packed bed in a solar heating system does not operate normally with constant temperature. During daytime different conditions like solar radiations, ambient temperature, collector inlet temperature and load requirements result in a variable collector outlet temperature. The optimum size of the storage system is a function of several system parameters such as storage temperature, material, storage heat losses, costs of the storage medium container, heat exchanger, cost of auxiliary energy and operating conditions such as insolation, ambient temperature, wind speed and solar fraction of the total heat load.

Energy can be stored in rocks or pebbles packed in insulated vessels. This type of storage system is used very often for temperatures up to 100 °C in conjunction with solar air heaters. It is reported to be simple in design and relatively inexpensive. Direct contact between the solid storage media and a heat transfer

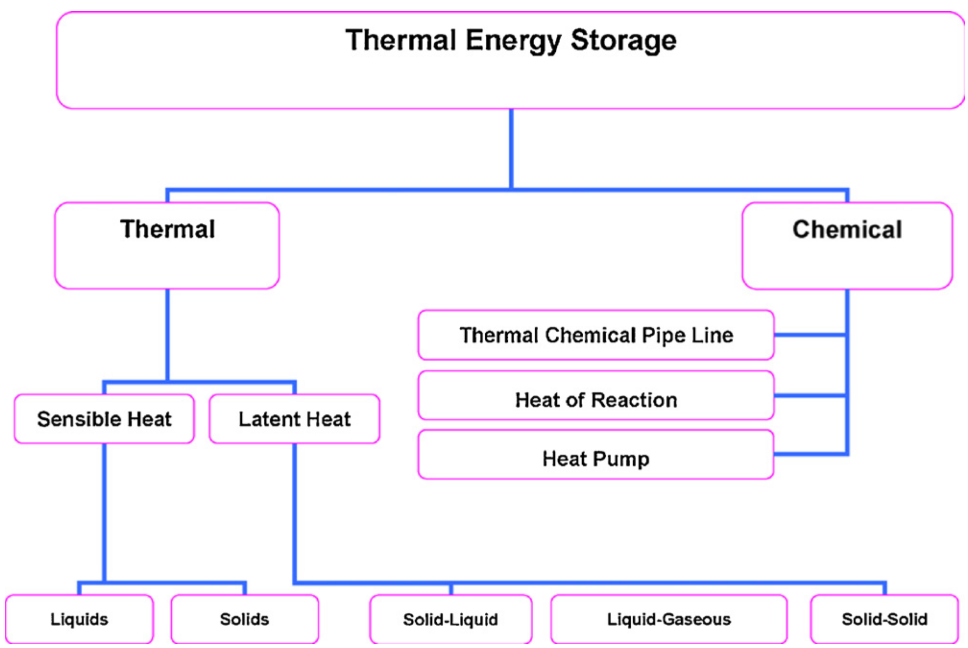

Fig. 2. Overview of thermal energy storage systems [1].

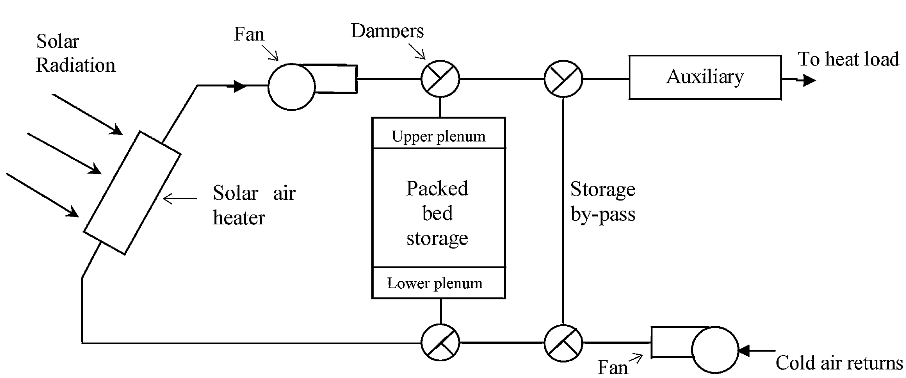

Fig. 3. Schematic of a packed bed energy storage system.

Table 1
Solid media properties of sensible heat storage materials [4].

Medium	Density (kg/m^3)	Specific heat (J/kg K)	Heat capacity $\rho c \times 10^{-6}$ (J/m^3 K)	Thermal conductivity (W/m K)	Thermal diffusivity $\alpha = k/\rho c \times 10^6$ (m^2/s)
Aluminum	2707	896	2.4255	204 at 20 °C	84.100
Aluminum oxide	3900	840	3.2760	–	–
Aluminum sulfate	2710	750	2.0325	–	–
Brick	1698	840	1.4263	0.69 at 29 °C	0.484
Brick magnesia	3000	1130	3.3900	5.07	1.496
Concrete	2240	1130	2.5310	0.9–1.3	0.356–0514
Cast iron	7900	837	6.6123	29.3	4.431
Pure iron	7897	452	3.5694	73.0 at 20 °C	20.450
Calcium chloride	2510	670	1.6817	–	–
Copper	8954	383	3.4294	385 at 20 °C	112.300
Earth (wet)	1700	2093	3.5581	2.51	0.705
Earth (dry)	1260	795	1.0017	0.25	0.250
Potassium chloride	1980	670	1.3266	–	–
Potassium sulfate	2660	920	2.4472	–	–
Sodium carbonate	2510	1090	2.7359	–	–
Stone, granite	2640	820	2.1648	1.73–3.98	0.799–1.840
Stone, limestone	2500	900	2.2500	1.26–1.33	0.560–0.591
Stone, marble	2600	800	2.0800	2.07–2.94	0.995–1.413
Stone, sandstone	2200	710	1.5620	1.83	1.172

fluid is necessary to minimize the cost of heat exchange in a solid storage medium. The use of rocks for thermal storage provides advantages such as (i) rocks are non-toxic and non-flammable, (ii) rocks are inexpensive and (iii) rocks act both as heat transfer surface and storage medium. The heat transfer between air and a rock bed is good, due to large heat transfer area, low effective heat conductance of the rock pile and small area of contact between the rocks. Theses factors contribute the advantage of low heat losses from the pile.

Hasnain [3] reported that solid materials such as rocks, metals, concrete, sand and brick can be used for low as well as high temperature heat storage. The pebble beds or rocks are generally used as storage material because of their low cost. Typically the size of rock used varies from 1 cm to 5 cm.

Among metals, aluminum, magnesium and zinc have been mentioned as suitable material. The use of metallic media is useful where high thermal conductivity is required and the cost is of the secondary importance. Solid industrial wastes such as copper slag, iron slag, aluminum slag and copper chips may be used as storage material for energy storage. Various metallic, refractory materials and different stones can also be used as storage material [4]. A list of various materials along with their properties is given in Table 1.

There have been many analytical and experimental studies done so far for the performance analysis of the packed bed. A detailed review on various studies done so far on packed beds is discussed below.

3. Analytical studies

The heat transfer to and from a flowing fluid to a packed bed has been the subject of many theoretical and experimental investigations since Schumann's original work [5]. He studied a liquid initially at uniform temperature passes lengthwise through a right, porous prism, initially at some other uniform temperature. He concluded that the sides of the prism are adiabatic and impervious to the liquid and the temperatures of both liquid and solid will be the functions of time and a distance between inlet and outlet. For a gas instead of a liquid, the problem became much more complicated but a dimensional method of treating the problem leads to results which may be very useful in practice. He presented one-dimensional two-phase model for packed bed system by ignoring the thermal capacity of the fluid, axial conduction in the fluid and axial conduction in the bed material.

The governing equations of the model are given as below:

(i) For fluids

$$\rho_a C_a \upsilon_a \frac{\partial T_a}{\partial \xi} = h_v (T_b - T_a) \tag{1}$$

(ii) For solids

$$\rho_b C_b \frac{\partial T_b}{\partial \tau} = h_v (T_a - T_b) \tag{2}$$

Using infinite series and Bessel functions Schumann [5] originally solved these equations for step change in inlet temperature of a semi-infinite packed bed initially at uniform temperature.

Pomeroy [6] identified the major parameters which control the thermocline broadening in sodium–iron storage system by investigating the special cases like ideal heat transfer, convective resistance effects, axial conduction effects and effect of non-uniform temperature in spheres for improving the volumetric heat capacity of a packed bed storage.

Klinkenberg [7], Ledoux [8] and Larsen [9] made efforts to facilitate the extraction of numerical information from the solutions by providing nomograms, extensive graphs and tabulations. These studies served well for hand computations. However, for simulating the entire system with the aid of a computer the method of graphs and tables became obsolete. Duffie and Beckman [10], Klein [11], Mumma and Marvin [12] made attempts to solve the governing equations for the packed bed by finite difference methods. This approach was also not free of difficulties, which required lot of time to compute the temperature distribution in the bed and increased the cost of computation. Hughes et al. [13] observed that the time to compute the temperature distribution in the bed might constitute a substantial fraction of computational effort of the simulation. Sowell and Curry [14] presented an accurate and efficient model based on convolution theory for replacing finite difference method in which differentials are removed from the simulation equation. In this study the inlet temperature varied as the insolation profile followed by flow reversal for heat extraction.

Saez and McCoy [15] presented a mathematical model for simulating the dynamic response of a packed column to an arbitrary time dependent inlet air temperature. It included features like axial thermal dispersion as well as intraparticle

conduction that have usually been neglected but can be important in solar energy applications. Energy loss to the surroundings was also neglected. They mentioned that if the value of Biot number (Bi) is large then intraparticle conduction effects could not be ignored. If $Bi << 1$ then intraparticle heat conduction is negligible and at any cross-section of the bed column, fluid and solid temperature will be same.

Balakrishnan and Pei [16] reported that the expected modes of heat transfer in a packed bed can be described as (i) the convective heat transfer from the walls of the packed bed to the fluid, (ii) the convective heat transfer from the particles to the fluid flowing through the bed; the conduction heat transfer from the walls of the bed to the particles constituting the bed, (iii) the conduction heat transfer between the individual particles in the bed and (iv) radiant heat transfer and heat transfer by mixing of the fluid. Authors mentioned that these heat transfer modes might interact with one another.

Fath [17] conducted an extensive study on different energy storage techniques and materials used in sensible heat storage systems. The author reported that large storage size usually required and the temperature swing created from the sensible addition and extraction of the energy were two major disadvantages in most sensible heat storage systems. Further, use of storage materials having a large thermal capacity decrease the size. The storage materials should have high thermal diffusivity. A large storage space besides occupying a large space and increasing cost also causes large thermal losses.

Solids have been reported as widely used storage materials in low temperature range. Extensive studies were carried out with the aim of exploiting the abundant storage capacity of rocks and ground. Other solid materials including metals can be used for thermal energy storage when they are formed into small balls or cylinders. Energy can be stored up to 800 °C in sand, cast iron, steel, aluminum, aluminum oxide, magnesium oxide and granite. Metals have good conductive characteristics and thus do not require a large heat transfer area. Sand on the other hand, need a large heat transfer area because of its insulative property. Water at high pressure up to about 140 bar, molten salts and liquid metals are used for sensible heat storage at intermediate and high temperatures.

Wyman et al. [18] reviewed the energy storage technologies for intermediate temperature storage. They reported that the total cost of a thermal energy storage unit was equal to sum of the energy related cost and the power related cost. The energy related costs included the storage medium, container, insulation and other items used for storage of heat, while heat exchangers, pumps, plumbing and heat transfer fluids needed to transfer heat to and from storage were included in the power related cost.

They reported that while using water as storage material above 100 °C, the storage tank must be able to contain water at its vapor pressure and the storage tank cost rises sharply with temperature beyond this point. The difficulties of vapor pressure of water and the limitations of other liquids can be avoided by storing thermal energy as sensible heat in solids. But large amounts of solids are needed than water since the heat storage density of solids is usually less than water. The cost of storage media per unit energy cost is not as low as for water, but is still acceptable for rocks. Direct contact between the solid storage media and the heat transfer fluid was found to be vital to minimize the cost of heat exchange in a solid storage medium.

Domanski and Fellah [19] focused on the advantages of utilizing thermo economic aspects in designing and operating thermal energy storage systems. The trade-off between cost of the irreversibility rate and that of the storage system formed the basis for the technique of thermo economic optimization.

Atear [4] presented a detailed coverage on the sensible heat storage techniques and materials generally used for storage. It was reported that sensible heat storage systems were simpler in design; however they suffer from the disadvantage of being bigger in size. For this reason, an important criterion for selecting a material for sensible heat storage system is its heat capacity. A variety of substances have been used in sensible heat storage systems. The choice of material depends largely on the temperature level of the application. Water being used for temperature below 100 °C and refractory bricks used for temperatures up to 1000 °C.

Hasnain [3] presented a review on various heat storage techniques and reported that sensible heat storage technique is simple and commonly used technique. He discussed the details of the development of available energy storage technologies and the materials used for storage. He reported that salty water and petroleum based oils and molten salts are other liquid storage materials except water. For low as well as high temperature thermal energy storage solid materials like, rocks, metals, concrete, sand and bricks can be used. The highest product in the list of solid materials is cast iron, which exceeds the energy density level of water. However, cast iron is more expensive than stone or brick and hence payback period is much longer. Pebble beds or rock piles are generally used as storage materials due to their low cost. Ceramic bricks, consisting of olivine, magnesite, microtherm or feolite; building mass and structural cement were reported to be most prevalent among the building materials.

Dincer et al. [20] studied different aspects of sensible heat storage systems. They reported that the selection of sensible heat storage system depends upon the storage period, economical viability and operating conditions. The economical justification has been given by the annual income needed to cover capital and operating costs to be less than that required for primary generating equipment. The storage efficiency was defined as the ratio of the energy that can be withdrawn from storage to the amount put into storage. The storage efficiency can be achieved up to 90% in a well-stratified water tank when fully charged and discharged on a daily cycle. Sensible heat storage has been identified as the most economical storage technology for building heating, cooling and air conditioning applications.

Ismail and Stuginsky [21] conducted an analytical study on possible fixed bed models for phase change materials and sensible heat storage and presented a detailed report on effects of various parameters on the performance. They reported that an increase in particle diameter reduces pressure drop, increases Nusselt number and hence the heat transfer. The variation in mass flow rate was reported to cause a corresponding variation in Reynolds number and Nusselt number. The fluids with higher thermal capacities were capable of transferring large amounts of energy and consequently have shorter thermal charging and discharging time periods. The relevant thermophysical properties of storage material were identified as thermal capacity and the thermal conductivity. For a bed of certain volume and diameter, the void fraction determined the quantity of heat energy that can be stored, the superficial area of heat transfer and the pressure drop along the bed axis. Hence, for a bed of certain particle diameter, a range of variation in void fraction can be obtained by varying the filling arrangement of the bed. A reduction in the void fraction leads to an increase in the mass of particles present in the bed, an increase in thermal storage capacity of the bed and also an increase in heat transfer area and pressure drop. Due to variation in the working fluid inlet temperature the exit temperature depends on the thermophysical properties of the working fluid, the storage material as well as the size of the solid particles. The wall heat losses from a storage tank results in a reduction in the heat storage.

Aly and El-Sharkawy [22] studied the effects of storage material properties on the thermal behavior of packed beds during charging. A transient one-dimensional two-phase model was used to describe the temperature fields in the air and solid media constituting the bed. They concluded that one of the main sets of parameters affecting the design of solid packed beds is the physical property of the solid phase used as storage material and the choice of material is particularly important.

They further reported that the increase in storage medium density considerably increases the rate of charging and the storage capacity of the bed, and decreases the solid temperature rise inside the bed. The thermal conductivity of the solid phase was having an intriguing effect on the packed bed thermal performance. It increases the charging rate and amount of energy stored, and causes a higher temperature rise throughout the bed for a certain charging period, beyond which this trend completely reverses. The specific heat of the storage material affects the thermal behavior of the packed bed in the same general manner as the density, where its increase causes a higher rate of charging and greater storage capacity and a lower prevailing temperature throughout the solid phase.

The steel packed bed exhibited a higher storage rate and capacity relative to the rock bed. Its thermal storage performance was also much better than that of aluminum bed except during first 2 h of charging where they showed comparable behavior. The aluminum bed, on the other hand, showed a superior storage performance compared with that of rock only during the first 6 h of charging. The variation of energy stored and spatial temperature distribution with time was obtained as shown in Figs. 4 and 5.

Crandall and Thacher [23] performed numerical simulations for solar energy storage with rock in stratified beds. They reported that the packed beds can have high degree of stratification and this was a major advantage. Stratification provides higher temperature at top of the bed and coolest at the bottom. This allowed the warmest air to be delivered from the top of packed bed. Warm air satisfied the load more efficiently. Stratification in a rock bed decreased during the later part of the day, with a decrease in solar insolation and hence with a decrease in the collector outlet temperature. A schematic of arrangement investigated by them is shown in Fig. 6.

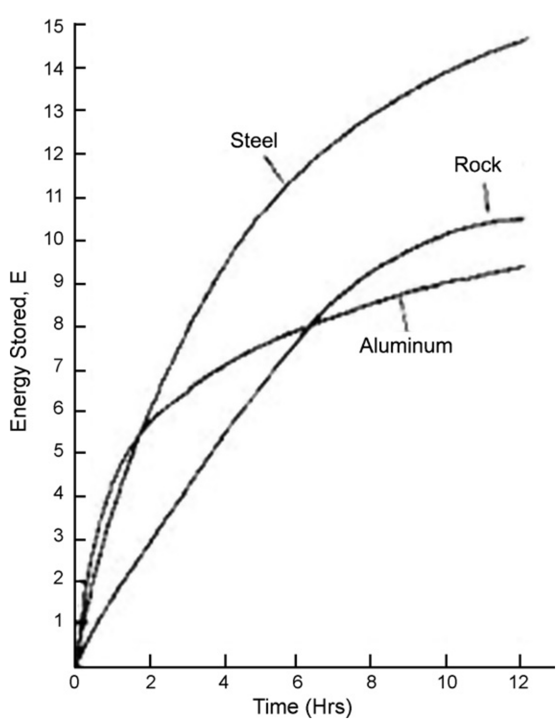

Fig. 4. Variation of energy stored with time for various storage materials [22].

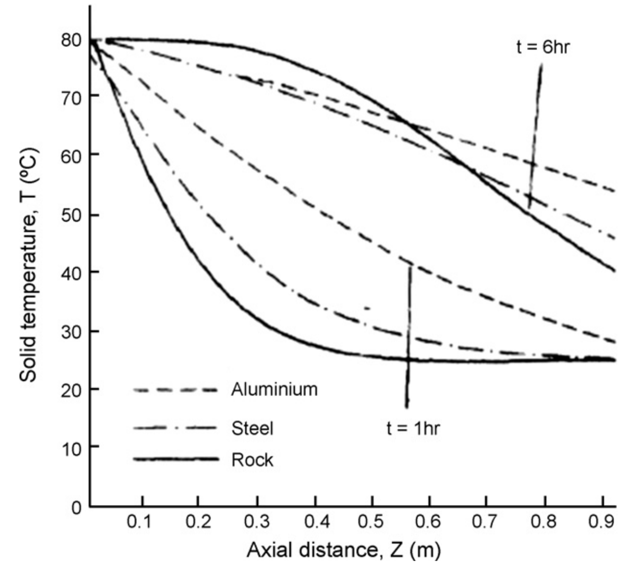

Fig. 5. Spatial temperature distributions for various storage medium packed beds at different charging times [22].

The characteristic governing equations of the model are as given below:

$$\frac{\partial T}{\partial t}+\frac{\partial T}{\partial x}=\frac{\partial^2 T}{\partial x^2} \tag{3}$$

and

$$-\frac{\partial T}{\partial x}=T_{\text{in}}-T \ \text{at}\, x=0; \quad \frac{\partial T}{\partial x}=0 \ \text{at}\, x=\propto \tag{4}$$

Based on a single-phase conductivity model of packed bed, analytical solutions were given in simple closed forms for a variety

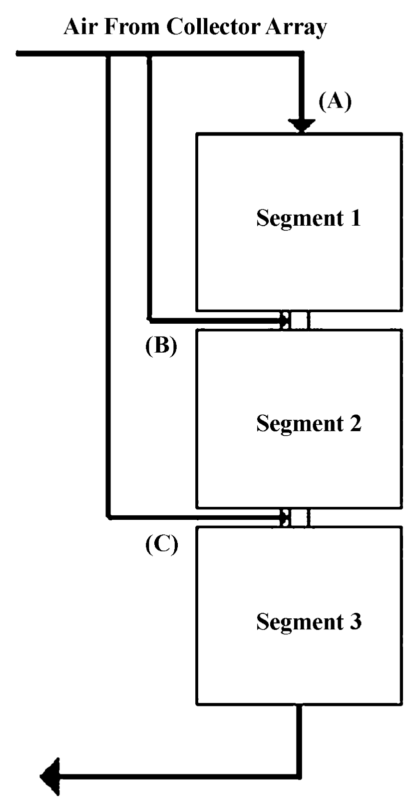

Fig. 6. Arrangement of the segmented tank system [23].

of inlet temperature conditions. The analytical solutions were reported to predict the long-term dynamic performance of packed beds and to device design procedures for utilization of air rock packed beds in thermal energy storage systems.

Maaliou and McCoy [24] presented a model for optimization of design parameters of a packed bed. The objective of the work was to device a method for the determination of the optimum velocity of air, column length and diameter, collection time and particle diameter, so that the packed bed yields the maximum net economic output. The net income was calculated as the difference between the economic value of stored heat and two cost factors, i.e. the capital cost and the operating cost. The dominating operating cost to be the pumping cost of circulating the air, which depends on the pressure drop through the bed. The column length had an optimum value since the pumping cost due to increasing pressure drop, as well as capital expenditure; counteracted the value of stored heat for longer columns. Similarly other variables had optimum values that maximized the net income. Any combination of these variables may be fixed and remaining variables simultaneously optimized by interactive direct search methods.

Choudhary et al. [25] conducted a theoretical analysis for optimization of design and operational parameters of a rock bed thermal energy storage device coupled with a two-pass single cover solar air heater. The optimization criterion was based on selecting those combinations for which the energy gain was maximum at lower cost. They reported that rich literature was not available on the design optimization of the rock bed thermal energy storage that kept the cost-effectiveness aspects in view. They investigated the effects of parameters like charging time, rock bed size, rock size, air mass velocity per unit bed cross-sectional area and void fraction on the total energy stored and the cost per unit energy stored in the rock bed for the winter climatic conditions of Delhi (India). They concluded that while designing and operating the rock bed, the value of air mass flow rate and the cross-sectional area of the bed should be selected depending on the requirements temperature for any particular application.

4. Experimental investigations

Furnas [26] probably conducted the first experimental study for heat transfer from a fluid stream to a bed of broken solids. He concluded that the coefficient of heat transfer varies along a straight line with gas velocity. The temperature of gas was reported to have a little effect on heat transfer coefficient and the degree of packing in a bed having a very large influence on resistance to fluid flow. A considerable variation in heat transfer for different materials was observed and the value of heat transfer coefficient decreased with an increase in particle diameter. There was no significant difference between the different iron ores studied when they were put on a common void basis.

Colburn [27] used granular materials, pebbles, porcelain balls and zinc balls of different sizes in the experimental study on heat transfer between air flowing through a filled tube with granular materials. They presented correlations for heat transfer coefficient and the heat transfer coefficient was found to be dependent on the mass flow rate of air and particle to tube diameter ratio.

Lof and Hawley [28] determined the heat transfer between air and loose solids in an experimental study. They concluded that the heat transfer coefficient increases along a straight line with an increase in airflow rate. However, it decreased along a straight line with an increase in the particle diameter (size of element). They reported that the data could be satisfactorily employed with other materials in general, if the rocks do not break into shapes having extreme dimensions of length to width or unless the surface is very rough.

Ergun [29] carried out a detailed analysis of the pressure drop associated with flow of a fluid through a packed bed. The author mentioned that there are number of factors determining the energy loss (pressure drop) in the packed beds. He reported that the pressure drop or total energy loss in a packed bed can be treated as the sum of viscous energy loss within the fluid itself, and kinetic energy loss with flow over the surface of the material particles. Friction factor was defined as the ratio of total energy loss to the kinetic energy loss.

Littman et al. [30] conducted gas particle heat transfer study in packed beds in low range of Reynolds number and concluded that the heat transfer coefficients obtained are reliable in the range from 6 to 99.2. In the range from 2 to 6, the Nusselt numbers was of the right order of magnitude. Dynamic thermal conductivities of the solid phase can be measured and interpreted by the methods discussed in this study.

Standish and Drinkwater [31] investigated air water flooding rates in packing columns. The values of sphericity were used to characterize the packing shape. The characterization of packing shape by sphericity was considered adequate for the purpose and sphericity was found to be simple and has a wide application. They reported that the shape of packing was a significant variable. Besides size distribution, the particle shape was most likely factor to affect the packing structure and its properties in randomly packed beds.

Chandra and Willits [32] found the pressure drop to depend on rock size, bed porosity and airflow rate. Coefficient of heat transfer was dependent on rock size and flow rate only. No influences of inlet air temperature or initial rock bed temperature on coefficient of heat transfer was found.

Courtier and Farber [2] used rocks in solar system for heat storage with packed beds. They concluded that a general and reliable method was needed while designing a packed bed; particularly to determine the most critical parameters as (i) air flow rate per unit face area of the bed, (ii) rock equivalent diameter and (iii) bed length and the bed face area. Two main variables, mass flow rate per unit face area of the bed and the rock equivalent diameter were shown to determine volumetric heat transfer coefficient. Finally the design considerations included the effect of fan power, total energy transferred, temperatures reached and noise control. The convective heat transfer coefficient increased along a straight line with an increase in the flow rate to particle diameter ratio, while the energy used by the blower decreased with a decrease in flow rate and with an increase in the particle diameter. An excellent agreement was found between experimental and theoretical curves obtained for expression of convective heat transfer coefficient.

Shitzer and Levy [33] carried out an investigation to study the transient behavior of a rock bed thermal storage system subjected to variable inlet air temperature. Pressure drop data were compared to values predicted by two previously published correlations and these were found to under predict the measured data due to the differences in the type, particularly the shapes of rocks used in different studies.

Beasley and Clark [34] reported that spatial variations in the void fraction have a significant influence on the dynamic response of both fluid and solid temperature. A numerical model has been developed that predicts the 2D transient response of both fluid and solid phases.

Hollands and Sullivan [35] concluded that in the case of the unwashed rocks, the fines (very small particles including dust) substantially increase the pressure drop across a particulate bed. The fines may form on rocks a coating, which would have apparent density lower than rocks, so a void fraction determined by mass measurement may give a higher value than the fraction actually available to the flowing air. Some designers of rock beds may

consider it highly desirable to remove all the dust from the rock particles before using them in rock bed.

Waked [36] studied the effect of height and rock size together with the flow rate and the pressure drop and the pumping power. It is concluded that the selection of the storage material must be based on material properties, type of application, available space and cost. The author reported that the rock could be successfully used as a storage material. It is well-stratified and more than 60% of the energy stored can be recovered at almost the maximum storage temperature.

Torab and Beasley [37] conducted second law efficiency analysis of sensible storage packed beds and concluded that the pumping energy increases as the effective diameter of storage material decreases and the total second law availability in the packing increases as effective diameter decreases. Availability also increases as the length of the packing increases. Hence, for efficient operation of a given packing volume, packed beds should use the smallest practical diameter spheres, the longest practical packing lengths, and the smallest practical packing dimensions normal to the direction of flow.

Sorour [38] concluded that the dimensions of the storage bed limit the storage efficiency in a pebble bed. Higher flow rate and/or very small particle dimension produce lower efficiency than with lower flow rate and with intermediate particle diameter for small size storage capacity.

Ammar and Ghoneim [39] reported that the heat storage in Tafla is slightly more than that for rock bed, a behavior that can be attributed to the relatively higher value of thermal conductivity and specific heat of Tafla. The particles with smaller diameter, i.e. with higher values of interphase surface area per unit volume cause a large degree of stratification in the bed. On contrary particles with large diameter degrade stratification.

Audi [40] tested small sized rocks for the stability analysis and their possible use as storage materials. Some of tested rocks such as Tarsand and Zeolite disintegrated under the operational environment. However, Jordian Basalt and Limestone demonstrated excellent stability during the tests and their storage properties were acceptable.

Sagara and Nakahara [41] suggested that the improvement of thermal performance and the reduction of friction in the packed beds are a trade-off in designing air based solar heating systems. The energy performance of solar heating systems using various kinds of storage materials were suggested to be investigated in order to prepare data with which designers can select the optimum storage material for their purpose. In case of large sized materials temperature gradient inside the solid cannot be ignored. It was found that thermal performance for a large size material like brick and concrete blocks was poor but they required less power supply to run the fans. They reported that the large size materials (Fig. 7) had almost the same thermal performance as small size materials in a solar heating system with a heat pump. If the bed is longer, the difference of fan energy between large and small materials becomes greater and then in that case, large size materials may be more favorable as storage materials. They mentioned that economic evaluation might become a decisive factor for the ability to utilize large size materials.

El-Kassaby and Ghoneim [42] analyzed natural soil for air based system and water for water based system in the sensible heat storage systems to study the variations in the amount of energy stored with time. They reported that the use of soil as storage material is possible instead of water, but additional collector area must be provided. Using a stratified air tank, the system efficiency can be increased by 5% and amount of heat stored by 25% over a day. The use of water system was found superior from the heat capacity point of view, but there were problems in maintaining the system.

Sanderson and Cunningham [43] conducted experiments on a vertical flow packed bed sensible thermal storage system to show the effect of altering equivalent sphere diameter of the packing on the degree of axial dispersion in thermally short packings. Experimentally measured average temperature wave velocities in the packing were presented. The significance of natural convection during heat exchange operation was also given. One-dimensional temperature profiles in the packing can be obtained using rectangular storage tanks in conjunction with flow distributors, which lead to a more efficient use of energy storing capacity of any given volume of packing by eliminating radial temperature dispersion.

Al-Nimr et al. [44] reported that earlier models proposed on packed beds were developed on a number of assumptions and the inlet fluid temperature was not varied with time. However, on actual practice a packed bed system receives the energy during charging from a heat source, which provides it with a variable inlet fluid temperature. They used rocks as storage material for sensible heat storage with water as heat transfer fluid. The model developed by them presented the prediction of the temperature distribution in the column for a variable inlet fluid temperature. Experimental results were compared with the results of the model.

Jalalzadeh-Azar Ali et al. [45] reported that previous research on packed bed was generally concerned with the thermal performance of the storage materials but ignored the stability aspects, which are particularly important for high temperature applications. In their experimental studies, each cycle consisted of a charging (storage) and a recovery (discharging) mode. The salt/ceramic composite pellets showed poor physical stability while the performance of zirconium materials was found to be excellent. The ZrO_2 medium offered a superior performance over the composite materials on an equal volume basis. This was attributed to the high thermal capacity per unit volume of zirconium material.

Hamdan Mohammed [46] investigated an integrated rock bed and solar collector system both theoretically and experimentally. The measured parameters were the inlet and outlet air temperatures, bed temperature, ambient temperature and solar insolation. Further the measurements were performed at different values of tilt angle and mass flow rate of air. It was found that the bed had a maximum storage efficiency of 46% when it was at an angle of 47° and a good agreement was found between theoretical predictions and experimental results.

Nsofor and Adebiyi George [47] conducted an experimental investigation of forced convection gas particle heat transfer coefficient and correlations were given for Nusselt number. The results covered a temperature range up to 1000 °C and Reynolds number between 50 and 120. The uncertainties in Nusselt number was reported to be as 10–30%.

Ozturk and Bascetincelik [48] reported that the solid materials were economically more attractive for high temperature heat storage than fluids and their volume requirements were nearly comparable. Direct contact between the solid storage medium and heat transfer fluid was vital to minimize the cost of heat exchange in a sensible heat storage system. The charging and discharging process of a thermal energy storage system was recommended to be analyzed in order to optimize the system efficiency.

Singh et al. [49] critically analyzed the works done on large sized storage elements and developed correlations for Nusselt number and friction factor for the data reported by Sagara and Nakahara [41]. They reported that the correlations developed in this study could be useful to investigate the performance of a packed bed solar energy system with in the investigated range of parameters. It was also concluded that the performance of the packed bed system with other shapes of material elements might be investigated.

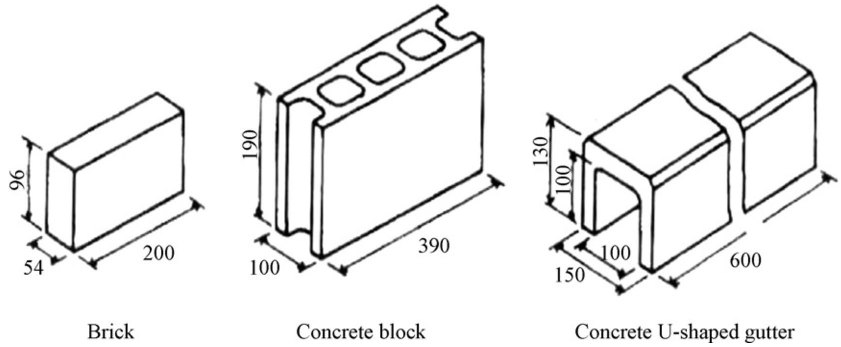

Fig. 7. Material elements used by Sagara and Nakahara [41].

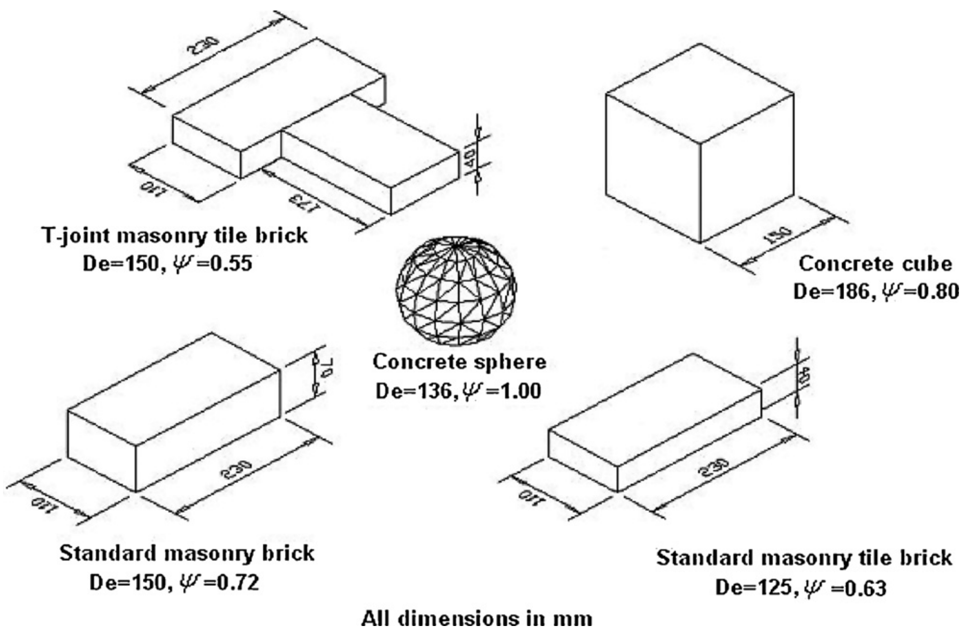

Fig. 8. Material elements used by Singh et al. [51].

Singh et al. [50] made an attempt to develop the correlations for Nusselt number and friction factor by using the earlier published data of masonry bricks having dimensions different from Indian masonry bricks. Based on the developed correlations, performance of the system having Indian masonry bricks as storage material was compared with the masonry bricks used in earlier works. The data presented by them was reported to be useful for predicting the thermal and hydraulic performance of packed bed system having masonry bricks as storage material (Fig. 8).

Singh et al. [51] conducted an extensive experimental study on different large sized storage materials. The material elements that were investigated included T-joint masonry tile bricks, standard masonry tile bricks, standard masonry bricks, concrete cubes and concrete spheres. The various shapes tested by them are as shown in Fig. 8. They reported that for a given value of Reynolds number, Nusselt number decreased as the value of sphericity was decreased from 1.00 to 0.80 and it was found to increase with further decrease of sphericity from 0.80 to 0.55 as is shown in Fig. 9. The change of flow patterns and area of contact available for heat transfer were supposed to be responsible for such a change in Nusselt number. With shift from cubical to other shapes with lower sphericity, it was observed that the flatness of surface increased with decrease in sphericity which caused more exposure of surface area for heat transfer and chances of higher turbulence intensity of fluid flow were more due to more number of sharp corners. This resulted in an increase in the value of Nusselt number as the value of sphericity decreased from 0.80 to 0.55. However, during fluid flow in the bed of spheres, fluid film remained in contact with the maximum portion of the surface of elements of spherical shape as compared to that for the other shapes, which resulted in an increase in the Nusselt number.

The results for the friction factor have also been given and the correlations were developed for both Nusselt number and friction factor as function of Reynolds number, sphericity and void fraction in order to predict the performance of the similar systems within the range of parameters investigated. The obtained results were compared with earlier studies and the validity of these correlations was found to be satisfactory. The presented Nusselt number and friction factor correlations can be used to predict the thermal and hydrodynamic performance of the actual packed bed solar energy storage system employing bed elements of highly non-spherical shapes.

Nallusamy et al. [52] reported that in case of constant heat transfer fluid temperature the mass flow had only a small effect on the rate of charging and the rate of heat transfer increases in direct proportion with the increase in inlet temperature of the heat transferring fluid temperature. The mass flow rate had a significant effect on the heat extraction rate. It was concluded that combined storage system gave better performance than the conventional

Table 2
Material, sizes and range of parameters of investigations by various researchers.

Sr. no.	Author	Materials used	Size	Correlation	Remarks
1.	Furnas [26]	Irregular solids of iron ores, coke, limestone, coal and blast furnace charge	Small size	$h = AG^{0.7}T^{0.3}10^{1.68f-3.56f2}/d^{0.9}$	Gas temperatures up to 1100 °C for iron ores and below 300 °C for coke and coal.
2.	Colburn [27]	Granular materials, pebbles, porcelain balls and zinc balls	A range of different small sized elements	$h = 8ac_{\mathrm{p}}z^{0.2}G^{0.82}$	–
3.	Lof and Hawley [28]	Gravel	4.8–9.6 mm, 9.6–12.7 mm, 19–25.4 mm, 25.4–38.1 mm	$h = 0.79\ (G/D)^{0.7}$	Void fraction: 0.426–0.454; air temperature: 38–121 °C
4.	Littman et al. [30]	Spherical particles of copper, lead and glass	0.5–2.0 mm	–	Void fraction: 0.431–0.532
5.	Standish and Drinkwater [31]	Glass spheres; coke particles; ceramic rings	16.7 mm; 22, 15.7, 9 mm; 12.7 mm	Sphericity (ψ) = surface area of a sphere with particle volume/surface area of particle	Void fraction: 0.41–0.59; sphericity: 0.53-1.0
6.	Chandra and Willits [32]	Washed river gravel and crushed granite	9.9–6.9 mm	$\frac{h_v D_e^2}{k} = 1.45\frac{(\rho\bar{v}D_e)^{0.7}}{\mu}$; $100 < \frac{\rho\bar{v}D_e}{\mu} < 1000$	Porosity range: 0.38–0.46
7.	Courtier and Farber [2]	Rocks	18–30 mm	$h_v = 700(G/d)^{0.76}$	Bed diameter: 570 mm length: 840 mm; flow rate: 0.4–2.0 m^3
8.	Beasley and Clark [34]	Soda lime glass spheres	12.6 mm	–	Void fraction: 0.364; bed to particle diameter ratio 30
9.	Hollands and Sullivan [35]	Thoroughly washed rocks	8.02–16.8 mm	$F_{\mathrm{r}} = 26 + 800/\mathrm{Re}_{\mathrm{r}}$ where, $\mathrm{Re}_{\mathrm{r}} = D_{\mathrm{r}}G_0/\mu$	Void fraction: 0.31–0.48
10.	Waked [36]	Rocks	20 mm, 25–50 mm	–	Void fraction: 0.36 and 0.47
11.	Sorour [38]	Rock and gypsum	12–30 mm	–	Influence of particle diameter, length of bed and flow rate on thermal performance of small SHES unit investigated
12.	Ammar and Ghoneim [39]	Rocks and Egyptian clay, Tafla	10–40 mm	Feasibility study on Tafla as storage material.	Optimum bed parameters: 210 mm for bed length, 19 mm for particle diameter and 900 kg/h for mass flow rate
13.	Audi [40]	Limestone, Tarsand, Zeolite and Basalt	Small size	Stability comparison of the soils available	
14.	Sagara and Nakahara [41]	Gravel, brick, concrete block and concrete U-shaped gutter	42 mm for ravel, 130 mm for brick, 100 mm concrete block, 100 mm U-shaped gutter	$\frac{\partial T^*_{s,m}}{\partial t^*} = L \times (T^*_a - T^*_{s,m})$; $K\frac{\partial T^*_a}{\partial t^*} + \frac{\partial T^*_a}{\partial x^*} = L \times (T^*_{s,m} - T^*_{sa})$	Void fraction: 0.38 for gravel 0.30–0.67 for brick, 0.46 for concrete block, 0.58 for U-shaped gutter
15.	El-Kassaby and Ghoneim [42]	Natural soil	Small size	–	Stratified tank void fraction: 0.24
15.	Al-Nimr et al. [44]	Rocks	33.9 mm	–	Void fraction: 0.43
16.	Jalalzadeh-Azar Ali et al. [45]	Zirconium oxide pellets	18.3 mm	–	300 thermal cycle with an operating temperature span of 25–980 °C.
17.	Nsofor and Abediyi George [47]	Zirconium oxide pellets	18.3 mm × 18.3 mm	$\mathrm{Nu}_{\mathrm{Dp}} = 8.74 + 9.34[6(1-\varepsilon)]^{a2}\mathrm{Re}_{\mathrm{Dp}}{}^{a2}\mathrm{Pr}_{\mathrm{f}}{}^{1/3}$	Void fraction 0.136; mass flow rate 100–610 kg/h
18.	Ozturk and Bascetincelik [48]	Volcanic material	54 kg/m^2	–	6000 mm × 2000 mm × 600 mm packed bed filled with 6480 kg of volcanic material
19.	Singh et al. [51]	Spherical and cubical element of concrete, masonry brick, tile brick and T-Joint	Large sized materials	$\mathrm{Nu} = 0.437(\mathrm{Re})^{0.75}(\psi)^{3.35}(\varepsilon)^{-1.62}[\exp\{29.03(\log\psi)^{2}\}]$; $f = 4.466(\mathrm{Re})^{-0.2}(\psi)^{0.696}(\varepsilon)^{-2.945}[\exp\{11.85(\log\psi)^2\}]$	Sphericity: 0.55–1.00; void fraction: 0.306–0.63; mass velocity: 0.155–0.266 kg/m^2

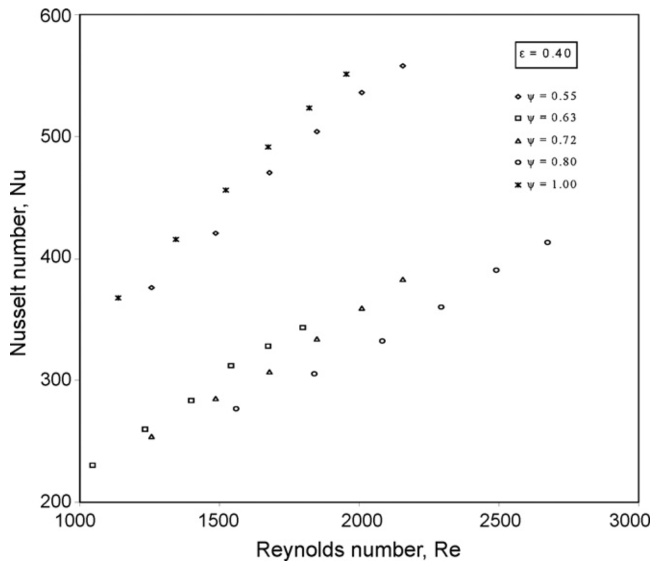

Fig. 9. Variation of Nusselt Number with Reynolds number [51].

sensible heat storage system when there was a direct mixing of the heat transfer fluid with the storage material.

The details of the types of material, packing material sizes and the correlations developed by various investigators in their experimental studies are summarized and given in Table 2.

5. Conclusions

Based on the literature survey conducted on packed bed solar energy storage system, it has been found that the packed beds were widely investigated both analytically and experimentally. A number of analytical studies were carried out in order to investigate the effects of various parameters on the performance of packed bed. The shape and size of the packing materials and void fraction are considered the important parameters that affect the performance of the system.

Only a few studies are reported for the optimization on the basis of cost-effectiveness. Investigators used different packing materials and developed correlations for heat transfer and friction factor as function of shape and size of the packing material. Use of large storage materials are investigated to reduce the fan power considerably, however very few studies were reported on the large sized storage materials. Further, no study on relatively medium sized storage elements is reported so far in order to have a compromise on the heat storage and the pressure drop in the packed bed storage system.

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